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Original Research

The Role of *Hydrocharitetum morsus-ranae* in Shaping the Chemical Composition of Surface Waters

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Abstract

The characteristic species of Hydrocharitetum morsus-ranae (*Hydrocharis morsus-ranae* and *Stratiotes aloides*) are used to determine the ecological condition of surface waters in many countries of the European Union. Aquatic and marshland plants play an important role in shaping the chemical composition of the littoral zone of eutrophic and mezotrophic water reservoirs. The aim of this study was to determine the influence of the extent of coverage of water surface by *Hydrocharicetum morsus-ranae* on the physicochemical and chemical properties of water inhabited by both plant species. Conducted field studies indicate that *Hydrocharicetum morsus-ranae* existed in reservoirs that are considered polluted due to the concentration of lead. The cumulation of mineral nutrients by plants inhabiting the studied reservoirs affected the chemical composition of the analyzed waters by limiting the influence of *Hydrocharis morsus-ranae* and *Stratiotes aloides* on the quality of these waters. The ecological range of occurrence of *Hydrocharis morsus-ranae* relative to most chemical water quality indicators is wider than that of *Stratiotes aloides*.

Keywords: *Hydrocharis morsus-ranae*, *Stratiotes aloides*, water reservoirs, rural watersheds

Introduction

The European frogbit (*Hydrocharis morsus-ranae*) and the water soldier (*Stratiotes aloides*) are characteristic species of *Hydrocharitetum morsus-ranae*. They are found quite commonly in Europe, the United Kingom, and Siberia, typically inhabiting regions that are sunlit and shielded from waves, and which are found in littoral zones of mezotrophic and eutrophic waters based on organic subsoils (lakes or their bays, oxbow lakes, canals) [1-11]. Both of these species are used to determine the ecological condition of surface waters in many countries of the European Union [12-14].

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These plants autonomously or conjointly inhabit littoral zones of water reservoirs. The distribution of plant communities in running and stagnated waters depends on physical and chemical conditions that are to a large extent related to the given region and landscape [15, 16]. The fact that the number of *Hydrocharitetum morsus-ranae* habitats and the area populated by these species has significantly changed over the last several years [5, 6, 17-19] can be attributed mainly to an increase in water eutrophication. In reservoirs of large phytocenotic discernment, *Hydrocharicetum morsus-ranae* coexist with other species of water and marsh plants, such as: *Elodea canadensis*, *Lemna minor*, *Nuphar luteum*, *Sagittaria sagittifolia*, and *Sparganium ramosum* [20], as well as *Nymphaea candida*, *Potamogeton natans*, and *Chara* *vulgaris* [21] or *Myriophyllum spicatum*, *Ceratophyllum demersum*, and *Phragmites australis* [22]. Numerous scientists emphasize that in reservoirs of different levels of eutrophication, the chemical composition of water is determined by the flora found both in the coastal area and the littoral zone [23-25]. Through the uptake of mineral nutritional compounds during their growing seasons, these plants lower the concentrations of these compounds in water [11, 26-28].

Despite the fact that in current legal regulations chemical indicators play a minor role in assessing the ecological condition of water [29], it is important to attempt to determine the influence of the extent of coverage of water surface by *Hydrocharicetum morsus-ranae* on the physical and chemical properties of water inhabited by both plant species. Such research will allow the ecological conditions of the inhabitancy of the European frogbit and water soldier to be further assessed in terms of chosen quality indicators.

Materials and Methods

These studies encompassed 12 water reservoirs of the Masurian Lake District, whose catchment basin use is dominated by agricultural land. Studied reservoirs can be described as shallow (with maximum depth not exceeding 3.0 m), containing water of low or moderate mineralization, and neutral or slightly alkaline pH (Table 1).

Analysis of the influence of the extent of littoral zone surface coverage by *Hydrocharicetum morsus-ranae* on the quality of water was undertaken during the growing season of 2009 in two isolated groups of water reservoirs. The first group (I) comprised reservoirs in which the European frogbit was found autonomously (sites 1-6), whereas the second group (II) comprised reservoirs conjointly inhabited by the European frogbit and the water soldier (sites 7-12). The analysis of phytocenotic composition concerned aquatic, marsh, wetland, and land plants inhabiting the littoral zones and coastal areas of the investigated reservoirs. A total of 328 phytosociological relevees were taken using the Braun-Blanquet method. The nomenclature of plant species was given according to Mirek et al. [30].

Measurements of the content of the following proteinogenic compounds were conducted in water samples: total Kjeldahl nitrogen, ortophosphate phosphorus, total phosphorus, and color. In order to determine these parameters, spectrophotometric methods were used in accordance with Polish standards (PN-73/C-04576/11, PN-C-04537-02, PN-EN ISO 7887). The measurements were conducted using a spectrophotometer Epoll 20 Eco. The turbidity [FTU] was indicated nephelometrically in centrifuged water samples. *In situ*, through the employment of multiparameter probe YSI 6600, the percentage of dissolved oxygen, its concentration, the turbidity [NTU], chlorophyll *a*, pH, and electrolytic conductivity of the waters sampled also were determined.

The content of the following metals: K, Na, Mg, Ca, Pb, Cu, Zn, Mn, and Fe, was determined after the mineralization of the water samples in nitric acid employing the atomic absorption spectroscopy technique, using a Solaar S AA spectrometer in three iterations.

The results obtained for the floristic studies and the measured water quality indicators were processed statistically in the program Statistica 9 PL. In order to assess the similarity of the results analyzed according to the groups of plants in the coastal zone and coastal waters, Ward's cluster analysis was applied (CA) [31]. The results of floral, physico-chemical and chemical water measurements were developed based on a one-factorial analysis of variance depending on the independent occurrence of the European frogbit or its coexistance with the water soldier. The significance of differences between means was determined by Tukey's test at p=0.05 ($LSD_{0.05}$). The value of Pearson's correlation coefficient was determined for the relationship between the percentile coverage of coastal area by particular plant groups and for the relationship between the percentile coverage of coastal area by the European frogbit and particular plant groups.

Results and Discussion

The studied water reservoirs, inhabited by *Hydrocharicetum morsus-ranae*, differed in surface area, the way in which the surrounding land was used, and the percentage surface coverage of the coastal area and littoral zone by water, marshland, wetland, and land plant species (Tables 1, 2). The composition by species of these plants is shown in Table 3.

The phytocenotic differentiation of the studied water reservoirs (Table 3) is similar to those reported in literature [9, 17, 20-22]. Sender [18] reported that the surface of Łukie Lake's bed (Łęczyńsko-Włodawskie Lake District) was almost entirely covered by *Hydrocharitetum morsus-ranae* in the 1990s and currently resembles the structure of macrophytes from the 1960s, when this plant community was formed in the littoral zone in the form of a ring surrounding the lake, and the only difference exists between the qualitative content. On the other hand, in Bikcze Lake *Hydrocharitetum morsus-ranae* occupied 28% of the phytolittoral zone's surface [19], and *Stratiotes aloides* was the dominant species. Gołdyn and Arczyńska-Chudy [17] point out that changes in water plant communities in aquatic ecosystems in agricultural areas, including the disappearance of *Stratiotetum aloidis*, are related to a large increase in the concentration of nitrogen in surface and ground waters observed in recent decades. Plant groups such as *Zannichellietum palustris* and *Ceratophylletum submerse* appeared in place of the ousted aquatic plants. It was also noted in this study that in the reservoirs not inhabited by *Stratiotes aloides* (Table 3), *Ceratophyllum demersum* occupied a greater surface area of the littoral zone. Smolders et al. [6] emphasize that in reservoirs studied in the Netherlands an increase in the concentration of sulfide anions in the sediment along with a simultaneous iron deficit, as well as high levels of ammonium cations and orthophosphate anions in the water and competition from other floating plant species, have significantly affected the disappearance of *Stratiotes aloides* from its habitats.

Table 1. Characteristics of the water reservoirs.

Site	Name	Geographical position	Surface area [ha]	Water properties		Dominant form of catchment area usage
				pH	EC*	
Reservoirs with *Hydrocharis morsus-ranae*						
1	Sętalskie Małe Lake	N:53º54'41" E:20º28'50"	12.5	7.77	281	agricultural
2	Sętal Pond	N:53º54'22" E:20º29'1"	1.6	7.49	315	agricultural
3	Bartołt Wielki Lake	N:53º46'53" E:20º49'8"	46.1	7.60	346	forestial-agricultural
4	Liznowskie Lake	N:53º46'2" E:20º33'18"	54.4	7.05	537	urban/agricultural
5	Gortek Lake	N:53º44'30" E:20º26'54"	4.9	6.97	70	forestial
6	Krumzy Lake	N:53º44'22" E:20º26'14"	38.4	7.00	402	forestial
Reservoirs with *Stratiotes aloides* and *Hydrocharis morsus-ranae*						
7	Łyna Oxbow Lake	N:54º5'40" E:20º26'15"	1.5	7.46	350	river valley/agricultural
8	Drwęca Oxbow Lake	N:53º28'4" E:19º36'6"	0.6	7.00	457	river valley
9	Potar Lake	N:54º7'10" E:20º22'49"	18.1	7.69	218	forestial
10	Lubajny Pond	N:53º41'18" E:20º2'37"	3.1	7.36	379	agricultural/barren
11	Choszczko Lake	N:53º46'28" E:20º52'7"	5.0	7.06	198	agricultural with buildings
12	Mały Kielbark Lake	N:53º35'56" E:20º51'57"	1.8	7.05	326	agricultural

*EC – electrolytic conductivity [$\mu S \cdot cm^{-1}$]

Table 2. The percentage of plants covering the subcoastal and littoral zones of water reservoirs (%).

Site	Aquatic plants		Marsh plants	Wetland plants	Land plants
	Other species	*Hydrocharitetum morsus-ranae*			
1	20.8	0.93	81.0	1.66	0.97
2	5.17	18.8	55.4	2.38	0.91
3	3.17	1.13	71.0	4.67	3.97
4	14.8	0.08	81.8	2.24	6.44
5	37.8	0.85	65.7	14.2	0.59
6	77.2	10.2	60.3	0.87	0.33
7	22.9	22.0	55.4	0.53	0.07
8	34.7	58.8	17.7	1.11	4.25
9	16.3	70.6	12.0	1.37	0.00
10	1.54	14.8	73.6	0.87	0.06
11	3.56	74.0	11.5	1.48	0.06
12	17.6	8.5	50.3	4.77	0.02
Average 1-12	21.3	23.4	53.0	3.02	1.47

Table 3. Species of aquatic and marsh plants occurring in littoral zones of water reservoirs – quantity by the Braun-Blanquet scale.

Species		Site											
		1	2	3	4	5	6	7	8	9	10	11	12
Aquatic plants	*Chlorophyta*				1	+							1
	Nuphar lutea							1					+
	Nymphaea alba			1									1
	Elodea canadensis		+										
	Stratiotes aloides							**4**	**4**	**3**	**3**	**4**	**2**
	Utricularia vulgaris												4
	Polygonum amphibium	+	1										
	Potamogeton natans		2									+	
	Ceratophyllum demersum	3	1	1						+			+
	Lemna minor		+	+	2	3	2	1	1	1		+	+
	Lemna trisulca			+		1		1		1		1	
	Spirodela polyrhiza			+	2	+	1	1		2			
	Sagittaria sagittifolia								2				
	Wolffia arrhiza					+	1						
	Hydrocharis morsus-ranae	**1**	**2**	**1**	**1**	**1**	**2**	**1**	**+**	**+**	**2**	**3**	**2**
Marsh plants	*Sparganium erectum*			1				+					
	Iris pseudacorus								+				
	Oenanthe aquatica					+							
	Glyceria maxima				+								
	Sium latifolium								+				
	Phalaris arundinacea		1			+							
	Typha latifolia		2	+	1	3	4	1			+		+
	Typha angustifolia			1									
	Rorippa palustris							+					
	Juncus effusus					1							+
	Scirpus sylvaticus						1			+			
	Equisetum fluviatile		+				1						
	Cicuta virosa				+					+			+
	Rumex hydrolapathum				+	1		+	+	+		+	+
	Acorus calamus				+				+				
	Phragmites australis	3		4	3				+	+	1		1
	Carex sp.		1			2	1	1			2	1	+
	Alisma plantago-aquatica		+										

The fact that a generally larger share of marsh plants in comparison to that of aquatic plants was observed in water reservoirs 2, 10, and 12 (Table 2) points to an advanced process of eutrophication and progressive succession of vegetation, which is a threat, especially to small bodies of water. The problem of shallowing and the disappearance of reservoirs in the areas intensively used for agriculture is an issue in Northern Europe [32], and is described extensively in Poland [17, 33-37].

Significant negative linear correlations between the percentage surface coverage by aquatic vegetation or *Hydrocharitetum morsus-ranae* and the percentage surface coverage by marsh plants were determined in the littoral zones of the studied water reservoirs (Figs. 1 and 2).

A higher value was found for the linear regression coefficient of the relationship incorporating the percentage water surface coverage by *Hydrocharitetum morsus-ranae*. The presence of *Stratiotes aloides* (y = 69.7-0.9.x, r = 0.92), and not of *Hydrocharis morsus-ranae* (y=11.2-0.1.x; r=-0,44), was a deciding factor for the significance of this relationship. Moreover, in the reservoirs in which both the studied plants were present (group II), the mean value of the percentage surface coverage of the littoral zone was found to be significantly lower (approximately twofold) than that in the sites in which the European frogbit existed without occurrence of the water soldier.

When it comes to the average surface coverage of the coastal area and the littoral zone by aquatic, wetland, and land plants, no statistically significant differences were found. The European frogbit generally inhabited reservoirs with large surface areas (Nos. 1, 3, 4, and 6) autonomously (Table 1).

The conducted Ward's cluster analysis of plants occurring in the coastal areas and littoral zones of the studied reservoirs indicates that aquatic and marsh plants may have the greatest impact on water quality (Fig. 3). Depending on the species, the availability of nutrients [38] and metals [39], and environmental conditions [40, 41], plants accumulate different amounts of metals, thus affecting their concentrations in water [23].

Świerk and Szpakowska [42] determined that dense strips of *Typha angustifolia* and *Phragmites australis* are a significant biogeochemical barrier to the free spreading of pollutants in bodies of water, due to their ability to accu-

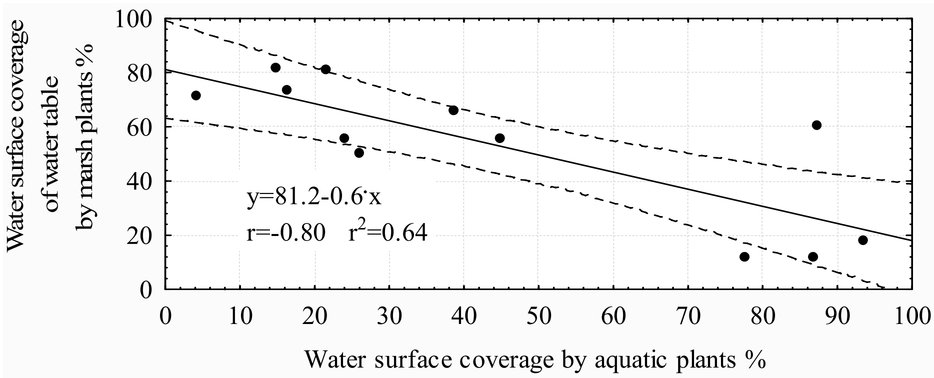

Fig. 1. Linear relationships between percentage water surface coverage by aquatic plants and by marsh plants.

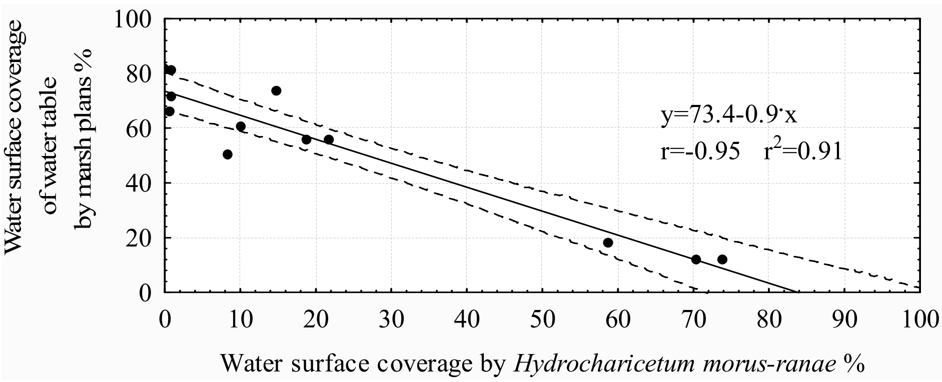

Fig. 2. Linear relationships between percentage water surface coverage by *Hydrocharitetum morsus-ranae* and by marsh plants.

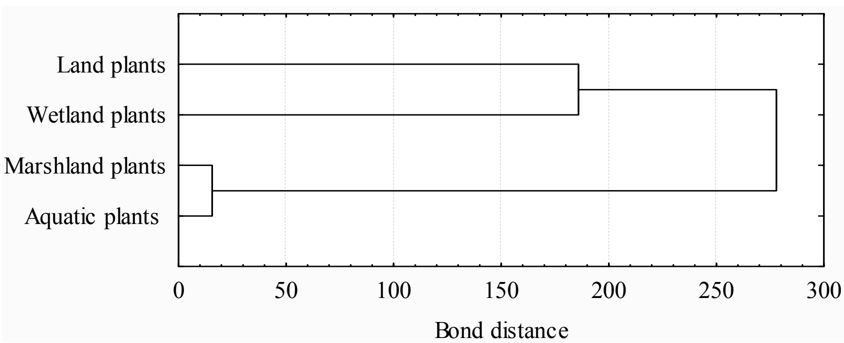

Fig. 3. A hierarchical clustering of plant ecological types in studied reservoirs.

mulate lead, copper and zinc. Species such as *Phragmites australis*, *Typha angustifolia*, *Typha latifolia*, *Phalaris arundinacea*, *Sparganium erectum*, *Glyceria maxima*, *Acorus calamus*, *Lemna minor*, *Elodea canadensis*, and *Ceratophyllum demersum* [43-47], which inhabited the studied bodies of water (Table 3), are used in constructed wetland wastewater treatment systems. Vymazal [44] reported that plants in hydrophytic wastewater treatment systems uptake approximately 10% of the nitrogen and phosphorus introduced with sewage. In systems of retreating sewage, the effect of removal of macro- and micronutrients is much higher.

In relevant literature, it is stressed that the metal content in the listed plant species, which inhabited the studied water reservoirs, varies over a wide range [11, 28, 41, 47]. Despite the high metal content in the dry biomass of the European frogbit (*H. mr.*) and the water soldier (*S.a.*) [11, 28], a low biomass of these plants may reduce the effectiveness of lowering metal concentrations in water.

Through analysis of the average metal concentrations in the studied groups of water reservoirs, it was found that significantly higher concentrations of zinc in water occurred in reservoirs inhabited by the European frogbit and the water soldier (Table 5). In the analyzed water tanks, no significant linear relationship was determined between the water surface coverage by the European frogbit and the analyzed values of water quality indicators. However, significant positive regressions were determined for the relationship between water coverage by hydrophytes and the concentration of manganese (y=0.0371+0.0021.x; r=0.84) and zinc (y=0.0014+ 0.0021.x; r = 0.84) in water, as well as a negative linear regression between water coverage by marsh plants and water turbidity (y=10,9-0,1.x; r=-0.82). An effect of the observed relationship in relation to zinc is an almost two-fold smaller percentage coverage of the coastal area and littoral zone of the studied water reservoirs by marsh vegetation, as well as a probable high content of zinc in the European frogbit and the water soldier (0.50÷2.2 $\mu gZn \cdot g^{-1}$ d.m. *H. mr.* or 0.20÷61.4 $\mu gZn \cdot g^{-1}$ d.m. *S. a.* [11]) compared to the Common reed (31÷337 ppm in *Phragmites australis* [48]).

In reservoirs inhabited conjointly by the European frogbit and the water soldier, a significant linear regression was only established between water coverage by hydrophytes and the concentration of lead in water (y= 0.0050+0.0002.x, r=0.83). This relationship was determined by the presence of *Hydrocharitetum morsus-ranae* (y=0.0035+0.0002.x, y=0.89). Literary data on lead indicate that the amount of this metal present in *Hydrocharis morsus-ranae* ranges from 0 to 67.2 $\mu gPb \cdot g^{-1}$ d.m., while the range of lead found in *Stratiotes aloides* is 2.12 to 11.5 $\mu gPb \cdot g^{-1}$ d.m. The high average percentage surface coverage of the coastal area and the littoral zone by hydrophytes in the second group of water reservoirs (Table 4), and the particularly significant role of *Stratiotes aloides*, due to its large biomass, can affect the accumulation of lead in these ecosystems. Decomposition of European frogbit and the water soldier leaves has an effect on the increase in the concentration of lead in water.

Table 4. Average percentage surface coverage of coastal areas and littoral zones by plants in particular groups of water reservoirs.

Water reservoir group	Average percentage surface coverage of coastal area and littoral zone %			
	Aquatic plants	Marsh plants	Wetland plants	Land plants
I	31.8	69.2	4.34	2.20
II	57.5	36.8	1.68	0.74
$LSD_{0.05}$	n.s.	26.0	n.s.	n.s.

n.s. – no significant

Hydrocharitetum morsus-ranae inhabited water reservoirs in which the concentrations of lead in the water exceeded the value of 7.2 ppb, thus indicating pollution by a substance especially harmful to the aquatic environment [29]. Through comparison of the obtained values for the water quality indicators (Table 5) with the data provided by Gałczyńska and Bednarz [11], it was found that the water reservoirs in the Masurian Lake District, which were inhabited only by the European frogbit as well as those in which the European frogbit coexisted with the water soldier, were characterized by lower average value of EC, and smaller average concentrations of primarily orthophosphates (V), potassium, magnesium, calcium, sodium, lead, copper, and zinc. Average concentrations of manganese and iron in the water were similar in reservoirs inhabited conjointly by the European frogbit and the water soldier.

The reason for the observed chemical and physico-chemical water properties was the accumulation of mineral nutrients by other species of aquatic and marsh plants existing in the vicinity of the European frogbit and the water soldier (Tables 2 and 3). Gałczyńska and Bednarz [11] found that the range of the ecological occurrence of the European frogbit in terms of most of the habitat's chemical agents was wider than for the water soldier. In terms of the concentrations of zinc, N compounds, and P compounds, the range of occurrence of the two water plants was the same. In the research conducted it was found that, when compared to the water soldier, the range of the ecological occurrence of the European frogbit was wider for EC, PO_4^{3-}, K, Mg, Ca, and Na, and narrower for $P_{og.}$, hue, turbidity, N_{Kjeh}, and chlorophyll *a*. With regard to the reaction of water and the concentrations of lead, copper, and oxygen in water, the range of occurrence of both plant species was the same.

Conclusions

1. *Hydrocharitetum morsus-ranae* existed in reservoirs that are considered polluted due to the concentration of lead.
2. The cumulation of mineral nutrients by plants inhabiting the studied reservoirs affected the chemical composition of the analyzed waters by limiting the influence of the European frogbit and the water soldier on the quality of these waters.

Table 5. Indicators of water quality in select groups of studied water reservoirs.

Parameter	Water bodies with *Hydrocharis morsus-ranae*				Water bodies with *Hydrocharis morsus-ranae* and *Stratiotes aloides*				$LSD_{0.05}$
	Mean	SEM	Min.	Max.	Mean	SEM	Min.	Max.	
pH	7.31	0.14	6.97	7.77	7.27	0.11	7.00	7.69	n.s.
EC [$\mu S \cdot cm^{-1}$]	325	63	70	537	321	40	198	457	n.s.
O_2 [$mg \cdot dm^{-3}$]	6.0	1.4	2.5	10.2	6.8	1.2	3.0	9.9	n.s.
Color [$mgPt \cdot dm^{-3}$]	114	31	44	241	144	44	48	347	n.s.
Turbidity [NTU]	3.4	1.0	0.0	6.5	4.6	1.6	0.0	9.6	n.s.
Turbidity [FTU]	3.2	0.6	1	5	5.7	2.8	1	18	n.s.
N_{Kjeh} [$mg \cdot dm^{-3}$]	1.38	0.15	1.12	2.10	1.20	0.17	0.80	1.44	n.s.
Chlorophyll *a* [$mg \cdot dm^{-3}$]	9.1	1.6	3.6	13.8	28.2	13.1	4.2	79.0	n.s.
PO_4^{3-} [$mg \cdot dm^{-3}$]	0.115	0.066	0.009	0.429	0.120	0.044	0.001	0.255	n.s.
$P_{og.}$ [$mg \cdot dm^{-3}$]	0.401	0.160	0.219	0.651	0.337	0.222	0.107	0.543	n.s.
K [$mg \cdot dm^{-3}$]	2.23	1.79	0.70	6.00	1.33	0.31	0.70	2.40	n.s.
Mg [$mg \cdot dm^{-3}$]	8.2	2.0	0.2	13.4	7.1	1.0	3.9	10.3	n.s.
Ca [$mg \cdot dm^{-3}$]	45.2	7.6	12.2	65.2	46.4	5.1	31.4	65.2	n.s.
Na [$mg \cdot dm^{-3}$]	7.55	8.58	1.30	24.8	5.23	1.91	3.20	8.30	n.s.
Pb [$mg \cdot dm^{-3}$]	0.011	0.003	0.0	0.022	0.006	0.003	0.000	0.019	n.s.
Cu [$mg \cdot dm^{-3}$]	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.003	n.s.
Zn [$mg \cdot dm^{-3}$]	0.003	0.001	0.001	0.005	0.009	0.003	0.002	0.020	0.006
Mn [$mg \cdot dm^{-3}$]	0.104	0.030	0.018	0.222	0.149	0.070	0.011	0.403	n.s.
Fe [$mg \cdot dm^{-3}$]	0.58	0.24	0.01	1.49	0.35	0.15	0.01	0.48	n.s.

SEM – standard error of the mean

3. The ecological range of occurrence of the European frogbit relative to most chemical water quality indicators is wider than that of the water soldier. With regard to the reaction of water and the concentrations of lead, copper, and oxygen in water, the range of occurrence of both plant species is the same.
4. The increase in the concentration of lead in water observed in the reservoirs cohabited by *Hydrocharis morsus-ranae* and *Stratiotes aloides,* along with a simultaneous percentage increase in the surface coverage by these species, is associated with the decomposition of *Hydrocharis morsus-ranae* and *Stratiotes aloides* leaves and the release of lead ions into the water.

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